ICESat range and mounting bias estimation over precisely-surveyed terrain

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Received 13 June 2005; revised 18 August 2005; accepted 21 September 2005; published 25 October 2005.

[1] Prior to the launch of the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and land Elevation Satellite (ICESat) in January 2003, topographic surveys were made by NASA's Airborne Topographic Mapper (ATM) over regions of the western United States and the Antarctic Dry Valleys to support calibration and validation of the range and pointing errors of GLAS lasers. Surveyed areas included terrain with large slopes, allowing pointing-bias estimation with as little as a few seconds of ICESat data. Range errors over sloping irregular surfaces are calculated by computing the expected GLAS return waveform and comparing it with the actual waveform. We conclude that the range bias is less than 2 cm and that pointing errors for the best available data set (Laser 2a) have rss errors less than 2 arcsec. **Citation:** Martin, C. F., R. H. Thomas, W. B. Krabill, and S. S. Manizade (2005), ICESat range and mounting bias estimation over precisely-surveyed terrain, *Geophys. Res. Lett.*, *32*, L21S07, doi:10.1029/2005GL023800.

1. Introduction

[2] With the prime objective of measuring ice surface elevation changes in Greenland and Antarctica to an accuracy of a few cm/yr, the Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud and land Elevation Satellite (ICESat) measures elevations of ~70 m diameter footprints spaced ~170 m apart along the satellite ground track. The range to the surface is combined with spacecraft orbital position and attitude to compute footprint geographic coordinates, i.e. where the laser beam hits the surface. For validation, we assume that both the GLAS range measurement and its pointing direction may be in error but that the orbital position has negligible error, based on state of the art orbit estimation [*Schutz et al.*, 2005]. Data time tags have been validated to a few microseconds [*Magruder et al.*, 2005] and are also a negligible error source. To validate both range and pointing throughout the satellite lifetime, GLAS measurements are required over independently-surveyed, unchanging topography for which a change in pointing produces a change in range. To obtain relatively uncorrelated errors in the estimates of range and pointing biases, we need surveyed surfaces with a variety of slopes. We first describe surveys over stable terrain areas suitable for validation throughout the ICESat mission, then explain how these measurements are used to estimate range and pointing biases, and finally present bias estimates for GLAS laser operations to date. After the premature failure of GLAS Laser 1 after operation for only 37 days, the remaining 2 lasers have been operated intermittently, surveying along the same 33-day sub-cycle of a 91-day repeat orbit during Oct/Nov, Feb/March, and May/June. These operational periods are referenced in discussions below by laser number and a letter for the period (e.g., Laser 2a).

2. Precise Terrain Surveys

[3] As discussed below, our bias estimation technique depends upon calculating a simulated waveform to compare with the GLAS waveform received at the satellite. The distribution of elevations within a GLAS footprint, needed to simulate the return waveform, was inferred from airborne surveys using the NASA/Wallops Airborne Topographic Mapper (ATM) which has been used for over 10 years for the measurement of surface elevations on ice sheets and land with a demonstrated sub-decimeter accuracy over flight lines of hundreds of kilometers [*Krabill et al.*, 2002]. Two different areas were surveyed: the Mojave Desert in California (centered around 35°N latitude and 244°E longitude) and the Dry Valleys region in Antarctica (centered around −77.5° S latitude and 162° E longitude).

[4] Mojave Desert: Parts of California's Mojave Desert were surveyed in June, 2001, in strips 100 km long and ~600 m wide along 24 planned ICESat orbit tracks. Vegetation along mapped strips is sparse, consisting mostly of desert shrubs. To maximize the density of elevation points, the Mojave ATM surveys used two lasers, with an overall swath width of 400 m. Each strip was flown twice with 50% overlap between swaths. The average footprint density in the overlap region was ~1 per 3 m^2, producing ~1000 ATM elevations in the nominal 70-m GLAS footprint. In order to hit the surveyed strips, ICESat was pointed up to a few degrees off-nadir. During the first operational period of Laser 2 (Laser 2a), ICESat data were acquired on 8 different days pointing to 7 different ATM-surveyed strips, with off-nadir angles up to 3.3°.

[5] Dry Valleys: The Dry Valleys region in Antarctica was mapped in December 2001. This area is mostly snow free and devoid of vegetation. Due to terrain constraints, the valley floors and edges were mapped with overlapping ATM swaths in directions approximately perpendicular to planned ICESat ground tracks, thus eliminating the need for ICESat off-nadir pointing except for passes near the ends of the valleys. The high Antarctic latitudes provide a higher spatial density of ICESat orbit tracks than the Mojave area.

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0094-8276/05/2005GL023800$05.00

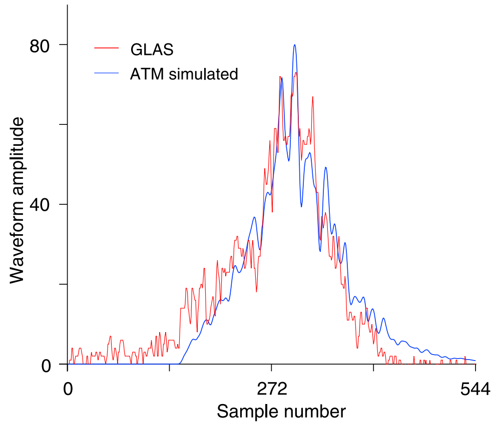

Figure 1. GLAS waveform, taken on 11 October 2003 at $10^h33^m13.523^s$ UTC, and ATM simulated waveform for Antarctic Dry Valley footprint centered at −77.3253° S latitude and 160.922° E longitude. Maximum correlation between waveforms is obtained by shifting simulated waveform 2.6 nsec (samples) to the left, corresponding to a range residual of −0.39 m.

For Laser 2a, usable validation data were acquired for 15 different ICESat passes.

3. Estimation Technique

[6] GLAS range measurements are computed from the time delay between pulse transmission and return, with corrections for atmospheric delays, solid Earth tides, and other effects. Over ice sheets and land, the return pulse is recorded in a range window of 544 1 ns bins. In "standard" ICESat processing, the position of the reflecting surface in the range window is based on a Gaussian fit to the return pulse. However, an irregular surface only means that the simulated waveform based on ATM surveys will be more complex than a simple Gaussian and there may be more uncertainty in comparison with the GLAS waveform. For the most accurate waveform computation, one also needs the reflectivity characteristics of the surface; however, these are not readily available and we assume here a constant reflectivity over the footprint.

[7] The simulated GLAS return-pulse waveform is calculated using: (a) the GLAS transmitted pulse width (~11 nsec at the $1/e^2$ point), (b) the measured transmitted pulse shape (variable from one laser to the next but more or less Gaussian), (c) the 3-d elevation distribution within the laser footprint out to a radius at which the beam amplitude drops to <0.5% of peak amplitude, and (d) the sensitivity of the GLAS telescope to returns within its field of view. This procedure is similar to that of *Harding and Carabajal* [2005], although the emphasis here is on matching pulse arrival times rather than waveform shapes since our surfaces contain little vegetation and displacements of surface position may make little change in the simulated waveform shape. The center of the ATM surface used for waveform simulation is always based on the current estimate (i.e., latest iteration) of GLAS pointing and could be twenty or more arcsecs away from the footprint location given on the GLA14 data file used. Figure 1 shows a sample of observed and simulated waveforms for a Dry Valley pass from a spot for which surface slope was >22°.

[8] To estimate pointing errors from differences between calculated and measured ranges, we need to calculate the sensitivity of ranges to changes in pointing. The GLAS laser is mounted on the spacecraft Optical Bench (OB) as described by *Schutz et al.* [2005] and the laser is pointed very close to the OB negative z axis as shown in Figure 2. Mathematically, the laser is mounted on axes rotated by an angle X about the OB x axis and by an angle Y about the OB y axis. In OB coordinates, the laser pointing direction thus has the components [sinYcosX, −sinX, −cosYcosX]. Our objective is to relate laser range errors to errors in the X and Y rotation angles. ATM positions are in earth-fixed coordinates, so the pointing direction and the satellite position were converted to ITRF (International Terrestrial Reference Frame) coordinates. Pointing directions were first transformed from OB to ICRF (International Celestial Reference Frame) coordinates using "obatt" files obtained from the University of Texas CSR web site (ftp.csr.utexas.edu/pub/icesat/pad) and then to ITRF coordinates using standard ICESat "ANC04" ancillary data files. The components of the vector p in Figure 2 can then be expressed as

$$\begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} = \mathbf{T}_{ITRF/ICRF}\mathbf{T}_{ICRF/OB}\begin{bmatrix} \sin Y \cos X \\ -\sin X \\ -\cos Y \cos X \end{bmatrix} \qquad (1)$$

where the transformation matrices go between the frames indicated by the subscripts.

6. Summary

[15] Validation of ICESat data over ATM-surveyed areas gives an estimated overall range bias of 0 ± 2 cm, with little indication of variations from one laser to another, or from one operations period to another. Considering that Mojave and the Dry Valleys are widely separated geographic areas, and with the Fricker result from Bolivia providing a third area, there is also no indication of geographic range bias dependence. Pointing-bias calibrations for the operational period with (nearly) complete refinement of laser pointing (Laser 2a) show rss errors less than 2 arcsec, again with the agreement between Mojave and the Dry Valleys indicating little geographic dependence of errors. Additional comparisons using ICESat data from all operations periods will refine assessments of measurement performance and improve measurements of elevation change.